Prospects and Challenges for a Large Water Cherenkov Detector for LBNE

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Abstract. The Long Baseline Neutrino Experiment (LBNE) is a proposed experiment that would send a beam of muon neutrinos from Fermilab to the DUSEL (Deep Underground Science and Engineering Laboratory) facility in South Dakota, a 1300 km baseline. One possible configuration for the far detector is one or more large water Cherenkov modules with a fiducial mass of at least 100 kilotons each. The prospects and challenges of such a detector, including the current design, will be presented.

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INTRODUCTION

The Long-Baseline Neutrino Experiment (LBNE) is a proposed experiment that would consist of a muon neutrino beam and near detector complex at Fermilab and a far detector located at a baseline of 1300 km at the Deep Underground Science and Engineering Laboratory (DUSEL) in Homestake mine in South Dakota. Currently, the detector technology for the far detector has not been decided. The options are a water Cherenkov detector, a liquid Argon detector, or a combination of both. The water Cherenkov option will be presented here.

Water Cherenkov detectors image the Cherenkov rings produced by charged particles traveling through water. The detectors are suitable a wide range of physics topics from the MeV energy scale to the GeV scale. The key detector parameters are the size and the light collection ability, which depends on the photomultiplier tube (PMT) quantum efficiency, photocathode coverage, and the attenuation length of the water. The technology is well-understood due to the successful operation of the Super-Kamiokande detector [1] in Japan for more than 15 years.

The detector requirements for a large water Cherenkov detector for LBNE are:

- At least 200 kilotons (ktons) of fiducial mass
- Multiple modules. The dimensions of a single module are limited by cavern engineering, light attenuation in water, and PMT pressure performance, so multiple modules are necessary to reach the desired mass. In addition, multiple modules allow 100% live time.
- Depth of at least 1000 meters-water-equivalent (mwe) for long-baseline neutrino oscillation physics (at least 4000 mwe for low energy physics)
- Photocathode coverage sufficient for particle reconstruction and identification. Increasing the coverage enhances the ability to do low-energy physics.
- Water purification to maintain purity

CURRENT DESIGN

The current LBNE design (assuming the water Cherenkov option) calls for two cylindrical 100-kton fiducial mass modules. Each module will be 63 m tall and 55 m in diameter, with a total water mass of 138 ktons. Each module will have approximately 50,000 PMTs, resulting in a photocathode coverage of around 20%.

Table 1 (reproduced from [2]) shows the required depth for a water Cherenkov detector at DUSEL for various physics topics. For long-baseline oscillation physics, the depth requirement is chosen such that the rate of neutrino beam events is comparable to the rate of cosmic events. The 4850 ft (4290 mwe) level of Homestake mine is deep enough for all physics topics, and is considered the baseline choice of location. The cosmic rate at the 4850 ft level is approximately 0.1 Hz per 100-kton module.

The current baseline choice for PMTs is a 10-inch tube from Hamamatsu. The PMT requirements include:

- quantum efficiency of at least 20%
- sensitive to wavelengths between 300 and 600 nm
- transit time spread (TTS) of $\sim$3.2 ns
- afterpulsing $<$ 5%, prepulsing $<$ 1%
- charge resolution of 50%

[1] for the LBNE Collaboration

TABLE 1. Depth requirements for a water Cherenkov detector at DUSEL for the physics topics of interest. This table is reproduced from [2].

Physics	Depth (mwe)
Long-baseline accelerator	1,000
Proton Decay	$>$ 3,000
Day/Night ^{8}B Solar ν	$\sim$ 4,300
Supernova burst	3,500
Relic supernova	4,300
Atmospheric ν	2,400

- gain of 10^7 at < 2000 V
- dark rate of 2500 Hz at a temperature of 13° C
- low flashing rate
- long term stability - both electrically and mechanically stable for up to 20 years
- pressure resistance up to 0.7 MPa (The pressure at the floor of the detector is 0.6 MPa).

There is a program underway to mitigate the risk of PMT failure due to pressure. To understand individual PMT response to pressure, data has been collected with a few different PMTs in a dedicated pressure vessel equipped with pressure sensors and a fast motion camera. The pressure was slowly increased until the bulb failed, and video was examined to determine the mode of failure. Since the detectors are expected to be in operation for many years, it is possible that some PMTs will eventually fail. The PMT assembly structure has been designed to prevent the shock wave produced by a PMT implosion from reaching neighboring PMTs. Large scale measurements of shock waves will be conducted by inducing PMT implosions in a large tank at a Navy facility in Rhode Island. The facility has a 15 m diameter vessel with a 500,000 gallon capacity capable of inducing pressure up to ∼0.7 MPa. The eventual goal is to test an entire module of PMTs to ensure the design of the mounting structure is sufficient to prevent a chain reaction of PMT failures.

The requirements for the water purification system include maintaining an attenuation length of at least 80 m and keeping the water temperature at 13° C. In the current design, it should take 100 days to fill one module and 20-25 days to circulate the entire volume of water of one module.

Dissolving gadolinium in the water would enhance the sensitivity to supernova relic neutrinos. The detection mode for these neutrinos is inverse beta decay, $\overline{\nu}_e p \rightarrow e^+ n$. The 8 MeV gamma cascade that occurs when a neutron is captured on gadolinium greatly improves the background rejection. Gadolinium-loading is not part of the baseline design, but the option is being kept open by ensuring that all materials in the detector and water circulation system are compatible with gadolinium.

The start of DUSEL construction is currently scheduled for 2014. The cavity excavation will take 2-3 years per cavity, while the detector construction will take around 2 years for each module. Production of 50,000 PMTs should take around 5 years.

EXPECTED PERFORMANCE

The performance requirements for an LBNE water Cherenkov detector include:

- vertex resolution of 30 cm for single ring events
- angular resolution of 1.5° to 3° over an energy range from 100 MeV to several GeV
- energy resolution for single muons and electrons much better than $4.5\%/\sqrt{(E)}$
- single-ring electron and muon separation with $>$90% success.
- the capability to recognize two rings with $>$90% efficiency when the opening angle between them is at least 20°.

These are modest goals largely based on actual Super-Kamiokande performance parameters. Water Cherenkov simulation and reconstruction tools are being developed for LBNE and are being validated against those used by Super-Kamiokande.

One of the main goals of LBNE is the observation of $\nu_\mu \rightarrow \nu_e$ oscillations. A ν_e appearance analysis will select single ring, electron-like events and reconstruct the neutrino energy assuming the interaction was charged-current quasi-elastic. The signal and background efficiencies used to estimate the sensitivity to ν_e appearance are based on a study using simulation and reconstruction tools from Super-Kamiokande, described in detail in [3]. This study provides a proof of principle, but has not been optimized for LBNE. The overall ν_e selection efficiency is 16% (28%) at 2 GeV (0.8 GeV). Figures 1 and 2 show the expected ν_e-selected reconstructed energy spectra for 5 years of running neutrino and antineutrino beams, respectively. The expected sensitivity to $\sin^2(2\theta_{13})$ is shown in Figure 3. These figures were made assuming $|\Delta m^2| = 2.4 \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) = 1$.

SUMMARY

In summary, the design of a water Cherenkov detector for LBNE is progressing, though the final configuration for the far detector for LBNE has not been decided. The

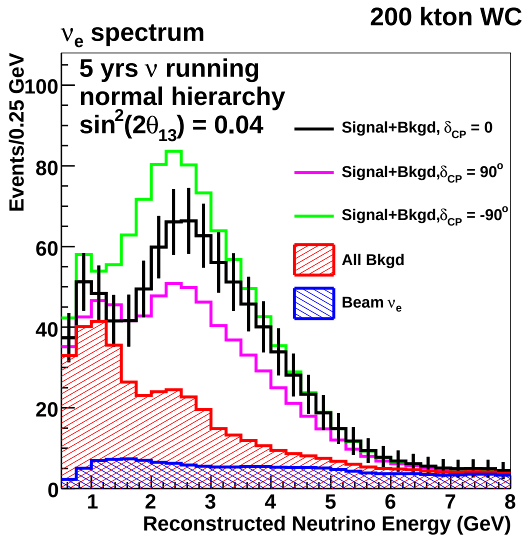

FIGURE 1. The expected ν_e-selected reconstructed energy spectrum for 5 years of running a 700 kW neutrino beam assuming $\sin^2(2\theta_{13}) = 0.04$, normal hierarchy, and three different values of δ_{CP}. The total background is shown in red, while the background only from ν_e's intrinsic to the beam is shown in blue.

current water Cherenkov design calls for two 100-kton fiducial mass modules at the 4850 ft level of Homestake mine. PMT studies, including analysis of pressure performance, are ongoing. The performance requirements for beam neutrino oscillations and other physics are well-understood due to experience from Super-Kamiokande.

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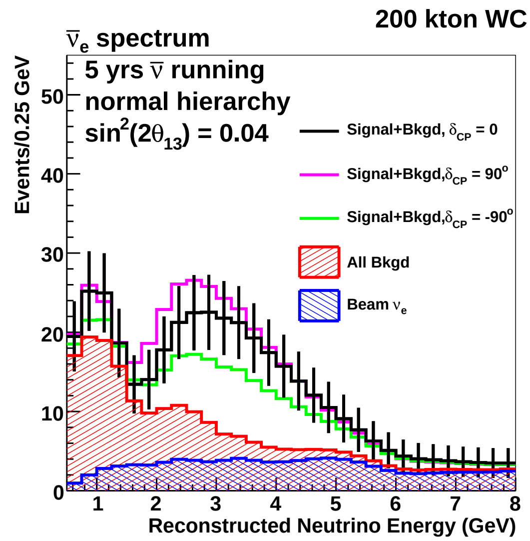

FIGURE 2. The expected ν_e-selected reconstructed energy spectrum for 5 years of running a 700 kW antineutrino beam assuming $\sin^2(2\theta_{13}) = 0.04$, normal hierarchy, and three different values of δ_{CP}. The total background is shown in red, while the background only from ν_e's intrinsic to the beam is shown in blue.

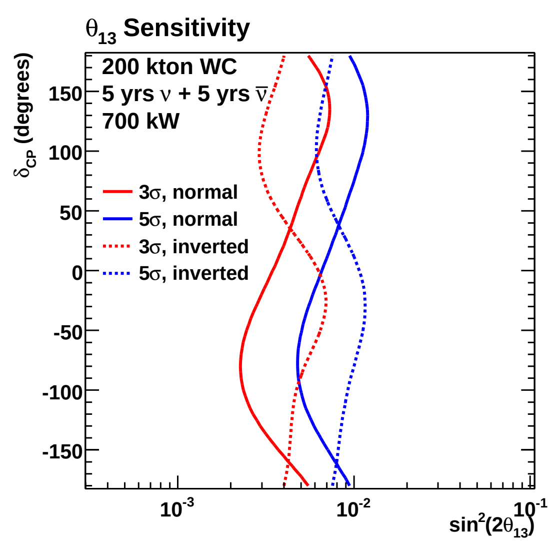

FIGURE 3. The sensitivity to discovering a non-zero θ_{13} at the 3- or 5-σ level as a function of $\sin^2(2\theta_{13})$ and δ_{CP} for both mass hierarchy possibilities. Values to the right of the curves would be excluded at the given confidence level.